SOFT SWITCHING CONVERTER USING CURRENT SHAPING

Cross Reference to Related Applications

Priority is claimed from U.S. provisional patent application Serial No.
60/372,172 entitled "Soft Switching Converter Using Current Shaping" filed April 12,
5   2002 in the name of Ionel D. Jitaru. That application is incorporated herein by
reference.

Field of the Invention

This invention relates to DC-to-DC converters, DC-to-DC inverters and AC-to-
DC converters (called generically herein "converters" or "power conversion circuits"),
10   in which primary switching elements switches at zero voltage and secondary rectifiers
have negligible reverse recovery losses.

Background of the Invention

There is a continuing industry demand for converters of increasing power
density, which means more power transferred in a given volume. A method for
15   increasing the power transfer through a converter is to increase the switching frequency
in order to minimize the size of the transformer and the capacitors. Using prior art
topologies such as forward or flyback, which employ "hard" switching techniques,
makes high frequency operation less efficient. The switching losses associated with
switching elements that turn on when there is a voltage across them are proportional to
20   the switching frequency. An increase in switching frequency leads to an increase in
switching losses and an increase in the level of electromagnetic interference (EMI).

In order to overcome limitations in switching speeds, the prior art has devised a
new family of soft transition. The U.S. patents Nos. 5,132,889, 5,126,931, 5,231,563
and 5,434,768 present several methods of accomplishing zero voltage across the
25   primary switches at switching. These patents are incorporated herein by reference.

Additional power loss in converters is due to the reverse recovery in output
rectifiers. During switching when a negative polarity voltage is applied to a rectifier
that is in conduction, the current through the rectifier will continue to conduct until all

the carriers in the rectifier's junctions are depleted. During this period of time, the current polarity will reverse the current flowing from the cathode to the anode, while the voltage across the diode is still positive from the anode to the cathode. The current flowing in reverse through the diode will reach a peak value referred to in literature as

5   Irrm. Further on, while the rectifiers' junction is depleting the carriers, the rectifier becomes a high impedance device. The current through the rectifier will decrease rapidly from Irrm level to zero. During the same time, the negative voltage across the rectifier will build up to high levels.

During the period of time when there is a negative voltage across the diode and

10   negative current is flowing through it, there will be power dissipation in the device. This kind of loss is referred in the literature as reverse recovery loss. The reverse recovery loss is proportional with the reverse recovery current Irrm, the negative voltage across the rectifier and the frequency.

The reverse recovery current Irrm, which is a key component in reverse recovery

15   loss, is a function of the type of device, the temperature and the current slope at turn off. The reverse recovery characteristics are worse for higher voltage rectifiers. As a result, the reverse recovery loss becomes a significant loss mechanism for higher output voltage applications. The reverse recovery current Irrm is directly dependent on the current slope at turn off. A "soft" or low current slope reduces the reverse recovery

20   current and as a consequence reduces the reverse recovery loss. To accomplish a very soft slope current at turn off, an inductive element has to be in series with the rectifier. The inductor element will prevent a fast current variation dI/dt. However, the presence of an inductive element in series with the rectifier will increase the negative voltage across the rectifier at turn off. The reverse voltage across the rectifier can reach very

25   high levels and can exceed the voltage break down of the device, leading to failure.

RC snubbers or complicated lossless snubbers can be added across the rectifier to reduce the reverse recovery loss and the voltage stress on the devices. This leads to complex circuits and this negatively affects efficiency and reliability. As a result of these limitations, the high voltage converters have had to operate at lower frequency in

30   order to reduce the power dissipation associated with reverse recovery.

Fig. 2A illustrates a standard full bridge phase shifted topology. The primary switching elements, M1, M2, M3 and M4 are controlled as depicted in the key

waveforms of Fig. 2B. During the time M1 and M4 are conducting, there is a positive voltage at the dot A in the secondary winding and the rectifier D1 is conducting. When M4 turns off, in the primary winding the current will continue to conduct, and its path will be through the parasitic capacitance of M3 and M4, discharging the parasitic

5   capacitance across M3 to zero and as a result creating zero voltage switching conditions. As a result, M3 will turn on at zero voltage. Further, M1 and M3 will be conducting. During this time, the primary winding of the transformer is shorted and the voltage in the secondary winding is zero. Both D1 and D2 will conduct during this time. The current through Lo will be split equally between D1 and D2.

10   At the moment when M1 turns off, the current will continue to flow in the primary discharging the parasitic capacitance of M2 towards zero. If certain conditions are met, M2 will turn on at zero voltage conditions. In any event, when M3 and M2 conduct, the polarity will change in the secondary winding. The change in polarity will force the current flowing through Lo to flow totally through D2 and the rectifier D1 will

15   be reverse biased. Due to the reverse recovery characteristic of D1, the current will flow in reverse through D1 as shown at point 5 until the carriers in the junction are depleted. After that the rectifier D1 will behave as a high impedance device. As a function of the current slope through D1 at turn off, which determines the reverse recovery characteristics of D1, and as a function of the parasitic inductive elements Lo

20   in series with D1, large voltage spikes will develop across D1 as shown at point 10 in Fig. 2B. This phenomenon will lead to reverse recovery losses in D1, when the reverse recovery current and reverse voltage will be present on the rectifier. In addition, these large voltage spikes developed across D1 may lead to voltage stress, which may exceed the rating of the device. For this reason, snubbing circuits may have to be employed

25   across D1, which will increase the power dissipation, increase circuit complexity, decrease reliability and decrease power density. The reverse recovery current associated with D1 will also create a "temporary short" across the secondary winding, preventing the resonant transition across M2 from achieving zero voltage switching conditions. The voltage ringing across D1 will also lead to increased EMI.

30   The losses associated with the reverse recovery of the output rectifiers are proportionate with the frequency. The trend towards miniaturization requires an increase in switching frequency, which leads to more reverse recovery losses. In

addition, in order to accomplish miniaturization, higher efficiency in converters is necessary to minimize heat. In conclusion then, there remains a need for a topology wherein the reverse recovery losses are eliminated, in this way allowing an increase in switching frequency without a penalty in efficiency.

5   Brief Summary of the Invention

This invention relates to a circuit and method to reduce the negative impact of the reverse recovery in the rectifiers in a secondary or output circuit of a converter, while allowing zero voltage switching on the primary switching elements. This technique works by forcing the current carriers out of each output rectifier of a

10   converter before a full reverse voltage from a transformer secondary is applied to it. This circuit and method of this invention operates by shaping the current through the output rectifiers using an additional injected or supplemental AC voltage superimposed on the main AC voltage induced in the secondary winding by the primary winding. In this implementation, even though the converter operates in continuous conduction

15   mode, the reverse recovery losses in the rectifiers, like those discussed above with respect to the spikes 10 in Fig. 2B, are totally eliminated.

Another major advantage of the proposed circuit of a preferred embodiment implementing this invention is that the current reflected in the primary is shaped to a trapezoidal form with a low dI/dt during the turn on of the primary switches. This

20   allows the completion of the resonant transition to zero voltage across the primary switching elements.

In the preferred exemplary embodiment, a converter or power conversion circuit has a power transformer with primary and secondary windings. A primary circuit connected with the primary winding is adapted to deliver a main primary current

25   through the primary winding of the power transformer, and a secondary circuit connected to the secondary winding is adapted to receive a main secondary current from the secondary winding and to deliver electrical power to a load. In the secondary circuit, at least one semiconductor unidirectional current conducting device, which can be a semiconductor diode or a synchronous rectifier or another such unidirectional

30   device, is connected to pass a main current passing also through an associated one of the

windings of the power transformer. An injection voltage source is connected to apply a supplemental reverse bias voltage to the semiconductor unidirectional current conducting device sufficient to terminate forward conduction in the device and to deplete carriers in junctions in the device. The depletion of carriers occurs prior to the

5   application of the full reverse voltage across the device such as results in reverse recovery losses.

In a preferred exemplary embodiment the power conversion circuit has a pair of the semiconductor unidirectional current conducting devices connected in series with an associated secondary winding. In that embodiment, the two unidirectional current

10   conducting devices alternately conduct through an output choke. Both devices have applied to them the reverse biasing voltage that terminates forward conduction and depletes junction carriers prior to the application of a higher level of reverse voltage such as causes reverse recovery losses.

Preferably in accordance with an exemplary embodiment of the invention, the

15   injection voltage source is connected with the power transformer's primary. In a specific embodiment, the injection voltage source is a further transformer connected in series with the primary of the power transformer. The auxiliary transformer preferably includes one winding in series with the primary winding of the power transformer and a secondary winding connected through a capacitor to ground. In one preferred

20   embodiment the primary circuit is a full bridge semiconductor switching circuit connected across the primary winding of the power transformer and the series connected winding of the auxiliary transformer. In this embodiment, the auxiliary transformer injects a triangular AC current that is applied to the junction of pairs of the transistor switches that form the input bridge. This assures zero voltage switching of those

25   switches regardless of load on the circuit. Where the secondary of the power transformer has a pair of secondary windings each series connected with one of the semiconductor unidirectional current conducting devices, those windings can be separate, distinct windings or the opposite halves of a center-tapped winding. As used herein, the terms "split winding" or "pair of windings" are not meant to distinguish

30   either a single center-tapped winding or two serially-connected windings.

The windings of the power transformer are preferably wound such that when the injection voltage produces the first supplemental reverse bias voltage, reverse biasing

the first of the pair of semiconductor unidirectional current conducting devices, the injection voltage also produces a first supplemental forward biasing voltage across the second of the devices, and when the injection voltage produces the second supplemental reverse bias voltage reverse biasing the second of the semiconductor unidirectional

5   current conducting devices, the injection voltage also produces a second supplemental forward biasing voltage across the first of the devices.

A DC input to the primary circuit can be a rectified AC or a DC input from a DC source. The bridge-connected switching devices are preferably four electrically controlled unidirectional semiconductor switches (MOSFETS for example) that are

10 electrically controlled to provide current in a first direction through the primary winding of the power transformer, then a short across the primary winding and its injection voltage source, then a current in a reverse direction through the primary winding, and then again a short across the primary winding and its injection voltage source. Across the secondary winding or windings is produced a first relatively high voltage forward

15 biasing a semiconductor unidirectional current conducting device, then a period of only the injection voltage-induced, relatively low secondary voltage reverse biasing the device, followed by a second relatively high reverse biasing voltage, and then another period of only the injection voltage-induced, relatively low secondary voltage, now in the forward bias direction.

20   It will be seen that in accordance with the method of the invention a reverse bias voltage is applied to a semiconductor rectifier to deplete at least one semiconductor junction of carriers in advance of each application of a higher reverse biasing power transformer secondary voltage excursion. This avoids substantial reverse recovery losses. This is accomplished by applying an injection voltage waveform to the primary

25 of a power transformer that couples an input or primary circuit to an output or a secondary circuit. Preferably the application of the injection voltage in accordance with the preferred method is by an auxiliary transformer having one winding connected to the primary of the power transformer and a second winding connected as described, i.e. through a capacitor to ground.

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Of course in each of the methods, the object is to apply the lower reverse biasing voltage to each semiconductor rectifier or other semiconductor unidirectional current

conducting devices in the secondary circuit so as to deplete the devices of carriers before a higher reverse biasing voltage is delivered to the device from the secondary of the power transformer to cause high reverse recovery losses. The depleted carriers are conducted by a secondary, conducting semiconductor rectifier.

5   The method of the preferred embodiment implementing the invention has the further advantage of adding an alternating current having a generally triangular waveform into the primary circuit to a set of semiconductor switching devices that make up a circuit that switches DC voltage to supply the power transformer primary. This current assures zero voltage switching by those switching devices.

10   The above and further objects and advantages of the invention will be better understood from the following detailed description of at least one preferred embodiment of the invention, taken in consideration with the accompanying drawings. In the several figures of the drawings like reference numbers denote like elements.

Brief Description of the Drawings

15   · Fig. 1A is a schematic diagram of a converter utilizing the power transfer methodology of the invention;

Fig. 1B is a series of plots of voltages and currents of the circuit of Fig. 1A versus time;

Fig. 2A is a schematic diagram of a converter wherein a prior art technique is
20 illustrated;

Fig. 2B is a series of plots of voltages and currents of the circuit of Fig. 2A versus time;

Fig. 3A is a schematic diagram of a specific exemplary embodiment of a converter configured in accordance with this invention;

25   Fig. 3B is a series of plots of voltages and currents of the circuit of Fig. 3A versus time; and

Fig. 4 is a schematic diagram of a further specific embodiment of a converter configured in accordance with this invention.

Detailed Description

The present invention addresses the goal of eliminating the reverse recovery losses while maintaining continuous conduction mode in an output choke of a converter. The general concept is described in connection with Fig. 1A. It consists in adding an

5   additional AC voltage source, which will generate a low voltage square waveform signal. Fig. 1A is a simplified schematic, and Fig. 1B illustrates key waveforms, both for the topology according to this invention. The circuit 12 of Fig. 1A is a typical full bridge, phase shifted topology, with an additional low voltage AC source 15 placed in series with a primary winding 16 of a power transformer 14.

10   In Fig. 1B, the conventional control signals for the primary switching elements M1, M2, M3 and M4 are also depicted in the plots so labeled. The injected AC voltage, Vinj, will alter the voltage Vsec in the secondary 13 of the transformer as is depicted by the dotted lines 18 in Fig. 1B.

During the time wherein M1 and M4 are conducting, the voltage induced in the

15   secondary winding has a positive polarity at the dot A and D1 is conducting. When M4 ceases to conduct, the injected voltage 17 of the source 15 produces the voltage 18 in the secondary winding with a low amplitude and negative polarity at the dot A. This will force the current out of D1 and into D2. Without the injected voltage 16 the current through Lo would be equally split between D1 and D2, as in the circuit of Fig. 2A.

20   At the time when M1 is turned off and M2 is turned on, the voltage induced in the secondary winding will change polarity, creating a negative voltage at the dot A. This will not change the current flow in the secondary, because D2 is already in full conduction, as indicated at 30 in Fig. 1B. Without the injected voltage at this time, both D1 and D2 would be in full conduction and, as illustrated in Fig. 2B, the negative

25   voltage 32 induced in the secondary winding would be applied to D1 leading to reverse recovery currents 5 and as a result reverse recovery losses. However, in accordance with the present invention, as shown at point 34 in Fig. 1B, conduction in D1 has already been brought to a halt by the reverse bias applied by the voltage 18 generated in the secondary by the auxiliary AC source 15.

Turning to Fig. 3A, in a circuit 19 implementing the invention, the additional injected voltage is provided by a small additional transformer 20 in series with the primary winding 16 and an additional capacitor 22. In Fig. 3B, the key waveforms of the circuit 19 are depicted. The additional magnetic element 20 has a primary winding

5   23 in series with the primary winding 16 of the main transformer and a secondary winding 24 in series with the capacitor 22 which is connected to ground. It accomplishes several tasks. First it creates the AC signal Vinj in series with the primary winding. As explained, this forces the output rectifiers out of conduction during the dead time, before the voltage polarity reverses in the secondary, thus preventing the

10   reverse recovery losses.

The second effect of this particular implementation is the creation of an additional triangular current Iinj in the winding 24. This is injected into the current in the primary circuit to form a trapezoidal waveform with low dI/dt. The current thus shaped is injected at the connection between M1 and M2, ensuring zero voltage

15   switching conditions even at light load. This is shown in Fig. 3B. There, when switch M1 turns ON at T_1, the injected current Iinj is flowing toward the switch M1, or in other words in the source to drain direction through M1 reducing the voltage across that switch. When M2 turns on at t_2, the current Iinj has reversed, M1 is OFF and Iinj at 36 is being drawn through the switch M2 in the source to drain direction reducing the

20   voltage on M2. The effect on M3 and M4 can be seen to be the same.

In Fig. 4, a circuit 40 is a further embodiment of the present invention. The diodes D1 and D2 of the previously described embodiments are replaced with synchronous rectifiers Sr1 and Sr2. One of the limitations associated with synchronous rectification is the conduction of the body diode, when the synchronous rectifier is

25   turned off before the voltage polarity changes. Ordinarily, current will flow through the body diode when the polarity changes in the secondary. The reverse recovery characteristics of the body diode are worse than ultra fast rectifiers. The advantage of a lower voltage drop on the rectifier is offset by the additional reverse recovery losses. This problem gets worse in higher voltage applications, larger than 24V for example,

30   where the reverse recovery loss mechanism is the dominant rectification loss. In the present invention, which eliminates the reverse recovery losses ordinarily occurring upon reverse biasing of the input switches by the full input voltage-induced secondary

voltage, it is very beneficial to replace the diodes with the synchronous rectifiers Sr1 and Sr2 of Fig. 4. Again the specific implementation shown assures zero voltage switching in the switching elements M1 - M4.

5   The foregoing descriptions of preferred embodiments are exemplary and not intended to limit the claimed invention. Obvious modifications that do not depart from the spirit and scope of the invention as claimed will be apparent to those skilled in the art.